International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 09 Issue: 12 | Dec - 2025 SJIF Rating: 8.586 ISSN: 2582-3930

Blockchain-Enabled Traceability in Agri-Food Logistics Networks: Systems, Applications, Challenges, and Future Potential

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Abstract

Ensuring traceability, transparency, and quality assurance in Agri-food logistics networks has become essential due to rising food fraud, globalized supply chains, and stringent regulatory standards. Blockchain technology offers a decentralized, tamper-proof, and real-time data-sharing infrastructure that enhances trust and accuracy across the supply chain. This paper investigates the principles, applications, and performance of Blockchain-enabled traceability in Agri-food logistics, focusing on vendor-managed inventory, smart contracts, sensor-embedded supply tracking, and Hyper ledger-based prototypes. Recent trends suggest a 25% rise in Blockchain adoption for post-harvest tracking by 2025. Case analyses of grape and coffee export chains highlight improvements in transparency, compliance, and disruption mitigation. Challenges such as interoperability, cost, data integrity, and scalability are also explored. Recommendations are proposed for effective Blockchain adoption in Indian Agri-food supply systems.

Keywords: Blockchain, Agri-Food, Logistics Networks, Traceability, Sensor

1. Introduction

Global agriculture supply chains have become increasingly complex due to cross-border movement of food products, diversified stakeholder involvement, and higher consumer expectations. Traditional traceability systems rely heavily on paper records, siloed databases, and manual inspections leading to inefficiencies, information delays, and risks of tampering. Food fraud, adulteration, and mislabeling continue to pose serious public-health concerns.

Blockchain technology, with its decentralized ledger and immutability, is emerging as a powerful tool for ensuring end-to-end visibility. Agri-food logistics networks can enhance traceability from farm to fork by integrating Blockchain with Iota sensors, smart contracts, and engineering-driven automation.

This research paper presents a comprehensive analysis of Blockchain-enabled traceability systems, covering their functionality, applications, challenges, and future potential.

Stage	Description and Key Elements	Flow
Agriculture	The initial stage, representing raw material production. Key elements shown are a farm, barn, windmill, crops, and a tractor.	Products move from the farm/field to the next stage.
Industry	The processing and manufacturing stage. Key elements shown are factories, silos, a loading dock, a truck, and workers. This stage converts raw materials into finished goods.	Processed/manufactured products move toward the market.

Consumers	The final stage where products and services are purchased and used. Key elements shown are city buildings, a Supermarket, other stores, shopping carts, and people (consumers).	Products are distributed to and purchased by the final customer.

Table 1. The Supply Chain

2. Background and Rationale

Blockchain technology emerged in agri-food logistics to address longstanding issues like opacity, fraud, and inefficiencies in traditional supply chains, were multiple intermediaries often obscure product origins and quality. Its decentralized ledger provides an immutable record of every transaction from farm to consumer, enabling real-time traceability that was previously fragmented or reliant on paper-based systems

2.1 Need for Traceability in Agri-Food Logistics

Blockchain-enabled traceability is essential in agri-food logistics due to the complexity of global supply chains involving numerous actors, which hinders farm-to-table visibility and exacerbates issues like contamination, fraud, and inefficiencies.

- Increasing food safety concerns
- Pressure from regulatory bodies (FSSAI, ISO 22000, Global GAP)
- Market demand for transparency, especially in premium exports (grapes, coffee, spices, dairy)
- Frequent disruptions in logistics (weather, storage failures, contamination, supply gaps)
- Rising food adulteration cases

2.2 Limitations of Traditional Systems

Traditional systems rely on fragmented, centralized data prone to errors, tampering, and delays in recalls, failing to ensure transparency on origins, quality, or sustainability.

- Fragmented Data
- Manual Record-Keeping
- Limited Real-Time Monitoring
- Data Manipulation Possibilities
- Slow Recall Procedures During Contamination Events

3. Blockchain Fundamentals Relevant to Food Supply Chains

Blockchain fundamentals relevant to food supply chains center on its distributed ledger technology, where timestamped, encrypted data blocks are linked chronologically and validated via consensus protocols among participants.

3.1 Core Features

Core features of blockchain fundamentals relevant to food supply chains include decentralization, immutability, transparency, and smart contracts.

- **Decentralization:** Shared access to all authorized stakeholders
- **Immutability:** Transactions cannot be altered

- **Transparency:** Each product movement is traceable
- **Consensus Mechanisms:** Ensures trustworthy validation
- **Smart Contracts:** Automated actions based on predefined rules

3.2 Types of Blockchain for Food Systems

Types of blockchain used in food systems include public, private, consortium, and hybrid.

- **Public Blockchain** (e.g., Ethereum) - open but less preferred due to cost
- **Private/Permissioned Blockchain** (e.g., Hyperledger Fabric) - secure, scalable, suitable for logistics
- **Consortium Blockchain** - shared control among industry partners

4. Blockchain-Enabled Traceability in Agri-Food Logistics Networks

Blockchain-enabled traceability in agri-food logistics networks uses a decentralized, immutable ledger to record every step of a product's journey from farm to consumer, integrating IoT devices like RFID, sensors, and QR codes for real-time data capture.

4.1 Addressing Food Fraud and Increasing Transparency

2025 trends indicate nearly **25%** increased adoption of Blockchain solutions for post-harvest tracking, especially in perishable commodities. Blockchain enhances:

- Certification Verification
- Origin Authentication
- Anti-Tampering Control
- Secure Storage of Digital Records

4.2 Vendor-Managed Inventory & Smart Contracts

Vendor-managed inventory (VMI) ensures timely replenishment and optimized logistics. Blockchain strengthens VMI by:

- Automating Approvals
- Triggering Payments Through Smart Contracts
- Reducing Stock Outages
- Minimizing Dispute Risks

Smart contracts ensure compliance with temperature limits, moisture content, and delivery timelines.

4.3 Engineering Insights: Sensor-Embedded Tracking

IoT sensors integrated with Blockchain enable:

- Real-Time Monitoring of Temperature, Humidity, Location
- Automatic Alerts During Deviations
- Improved Post-Harvest Handling
- Predictive Analytics for Spoilage Reduction

Sensor-embedded pallets, RFID/QR codes, and GPS trackers provide unbroken digital records from

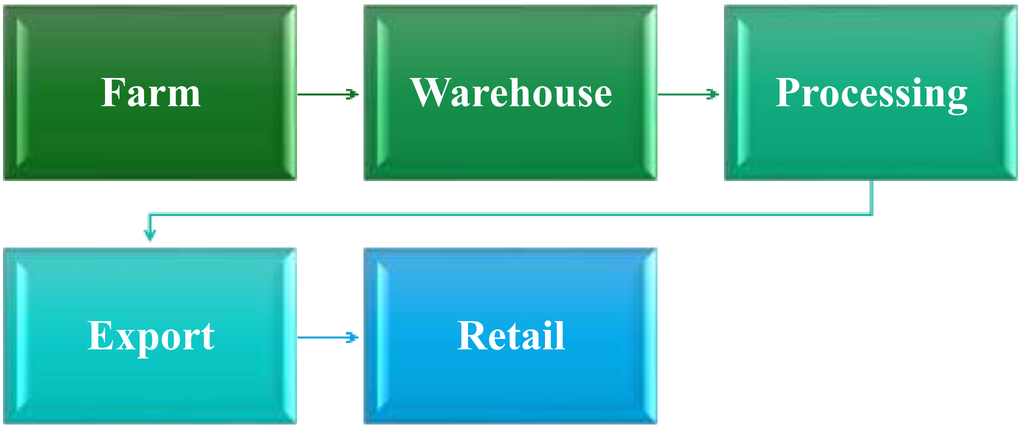

Fig. 1: Block diagram of Sensor-Embedded Tracking

4.4 Prototyping with Hyperledger

Prototyping with Hyperledger involves building proof-of-concept applications using Hyperledger Fabric, a permissioned blockchain framework ideal for enterprise scenarios like agri-food supply chains.

Hyperledger Fabric enables:

- Creation of Chain Codes (Smart Contracts)
- Private Channels for Sensitive Commodity Data
- Identity Management for Exporters, Farmers, Testing Labs
- High Throughput for Logistics Data

Prototype studies on grape and coffee chains show improved:

- Traceability Speed
- Export Compliance
- Certification Transparency
- Buyer Trust

Table 2. Blockchain-Enabled Traceability in Agri-Food

Stage	Data Capture	Supporting Tech	Blockchain Block Created
Farm	Planting, Fertilization, Fertilizer, Harvest, Certifications	IoT Sensors, QR Codes	Origin Block
Processing	Washing, Cutting, Packaging, Ingredients	Processing Parameters (Temperature, Batch #)	Processing Block
Distribution	Shipping, Shipping Routes, Storage Conditions	GPS, Temperature /Humidity Sensors	Shipping Block
Retail/Consumer	Arrival, Shelf Placement, Purchase	Retail Scanner App, Shipping QR Scan	—

5. Traceability Architecture for Agri-Food Chains

5.1 System Components

System components of traceability architecture for agri-food chains typically include data capture devices, blockchain/distributed ledger, smart contracts, off-chain storage, centralized databases for identifiers, and user interfaces.

- Blockchain Ledger
- IoT Sensors (Temp, Humidity, CO_2, GPS)
- Mobile/Web Dashboards
- Smart Contracts
- Digital Quality Certificates (Lab Reports, GAP Certifications)

5.2 Data Flow

Data flow in traceability architecture for agri-food chains follows a sequential path:

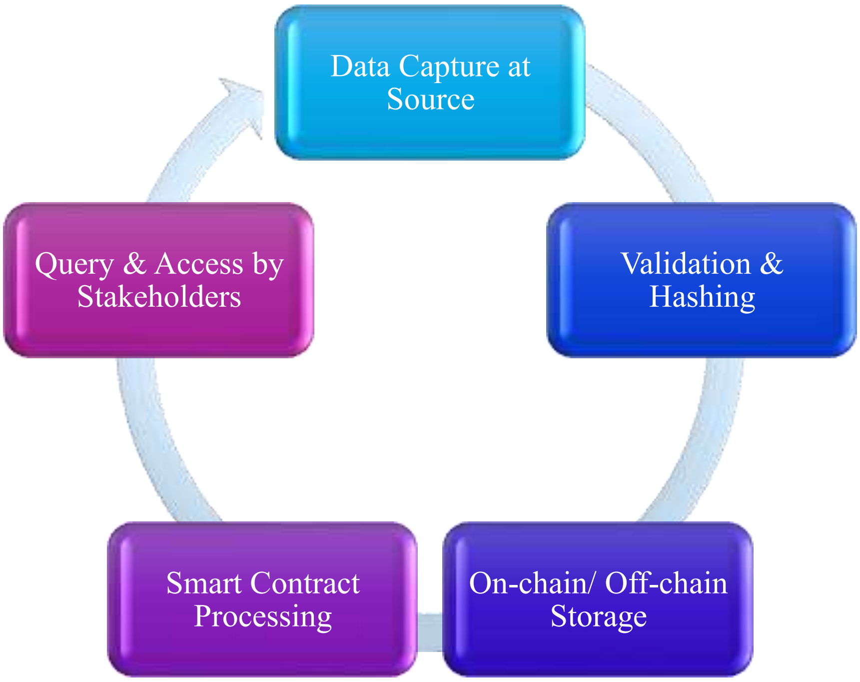

Fig. 2: Data Flow in Traceability Architecture

1. Farmer Inputs Production Data
2. Post-Harvest Center Updates Handling Details
3. Sensors Log Environmental Data
4. Processors Log Quality Tests
5. Exporters Record Packaging, Fumigation, And Transport
6. Importers Verify Documents
7. Retailers Track Shelf Life

6. Case Study: Grape Export Chain (India–EU)

GrapeNet is APEDA's blockchain-integrated traceability system for Indian grape exports to the EU, developed after 2003 rejections due to pesticide residues, enabling farm-to-fork tracking.

6.1 Key Issues Before Blockchain

Key issues in agri-food traceability before blockchain included lack of transparency, fragmented data, vulnerability to tampering, and inefficient recalls due to centralized, manual systems.

- Paper-based residue certificates
- Delays in verifying cold chain integrity
- Fraudulent documentation
- Rejected consignments

6.2 Blockchain Implementation

Blockchain implementation in agri-food supply chains follows structured phases: platform selection, network setup, IoT integration, smart contract development, data modeling, and deployment with testing.

- Hyperledger Fabric network
- QR codes on grape crates
- Continuous temperature monitoring sensors

6.3 Outcomes

Blockchain implementation in agri-food supply chains yields enhanced transparency, faster traceability, cost reductions, and improved food safety through immutable records and automation.

- 40–50% faster certification checks
- 100% digital traceability from farm to port
- Reduced export rejection rates
- Higher buyer confidence

Year	Adoption (%)
2020	2%
2021	5%
2022	9%
2023	18%
2024	27%
2025	38%

Table 3. Blockchain Adoption for Agri - Food Traceability

7. Case Study: Coffee Export Chain

Launched with TechnoServe, it tracks beans via IoT sensors, QR codes, and mobile apps, recording farm practices, harvest, processing, and export data on a permissioned ledger to verify sustainability and quality certifications.

7.1 Pre-Blockchain Problems

Pre-blockchain problems in agri-food supply chains stemmed from manual, paper-based records, centralized databases, and fragmented systems across multiple intermediaries, leading to opacity and unreliability.

- Mixing of low-grade beans
- Difficulty verifying origin
- Loss of identity during transport
- Unreliable organic certification

7.2 Blockchain Application

Blockchain applications in agri-food supply chains primarily focus on traceability, smart contracts, provenance verification, and automated transactions to enhance transparency and efficiency.

- Unique batch ID for each lot
- Smart contract verification
- Sensor-based tracking in wet/dry processing

7.3 Impact

Blockchain significantly impacts agri-food supply chains by enhancing transparency, reducing recall times from days to seconds, cutting costs via automation, and boosting food safety and trust.

- Protected authenticity of specialty coffee
- Faster settlement between farmers and exporters
- Verified certification trail

8. Comparative Analysis: Blockchain vs Traditional Systems

Blockchain outperforms traditional traceability systems in transparency, integrity, and recall speed, while traditional systems remain simpler but more vulnerable to errors, tampering, and delays:

Feature	Traditional System	Blockchain-Enabled System
Data Storage	Siloed, manual	Distributed , Secure
Transparency	Low	High
Fraud Risk	High	Very Low
Recall Speed	Slow	Immediate
Data Tampering	Easy	Nearly Impossible
Cost Over Time	High	Moderate/Low
Consumer Trust	Limited	Strong

Table 4. Comparative Analysis: Blockchain vs Traditional Systems

Section	Details
Tackles Food Fraud & Transparency	25% blockchain adoption rise for post-harvest tracking in 2025
Sensor-Embedded Supply Tracking	Farm → Post-harvest → Storage → Processing → Transport → Export → Retail
Vendor-Managed Inventory & Smart Contracts	Real-time visibility, automatic stock updates, compliance, disruption mitigation
Prototype with Hyperledger	Applied to grape & coffee export chains; faster verification, fewer rejections

Table 5. Comparative Analysis: Blockchain vs Traditional Systems

9. Benefits of Blockchain in Agri-Food Logistics

Blockchain in agri-food logistics improves traceability, food safety, efficiency, and trust across the chain from farm to consumer.

9.1 Enhanced Traceability

Enhanced traceability means having deeper, faster, and more reliable visibility of a product's journey across the supply chain, beyond what basic "one-step-forward, one-step-back" tracking provides.

- Faster identification of contamination points.

9.2 Trust and Transparency

In agri-food logistics, trust and transparency refer to all stakeholders being able to rely on shared information about products and seeing clearly how food moves through the chain, without needing to blindly rely on intermediaries.

- Buyers and consumers access verified information.

9.3 Reduced Losses and Spoilage

Reduced losses and spoilage refer to lowering the amount of food that becomes unsellable or unsafe due to damage, temperature abuse, delays, or poor handling across the supply chain.

- Sensor-based monitoring prevents temperature abuse.

9.4 Compliance and Certification Automation

Compliance and certification automation uses smart contracts on blockchain to automatically verify and enforce regulatory standards, quality certifications, and documentation in agri-food logistics without manual intervention.

- Smart contracts simplify regulatory approval.

9.5 Improved Logistics Efficiency

Blockchain improves logistics efficiency in agri-food chains by providing real-time visibility, automating coordination, and optimizing resource use through shared, immutable data across stakeholders.

- Accurate forecasting and reduced bottlenecks through real-time data.

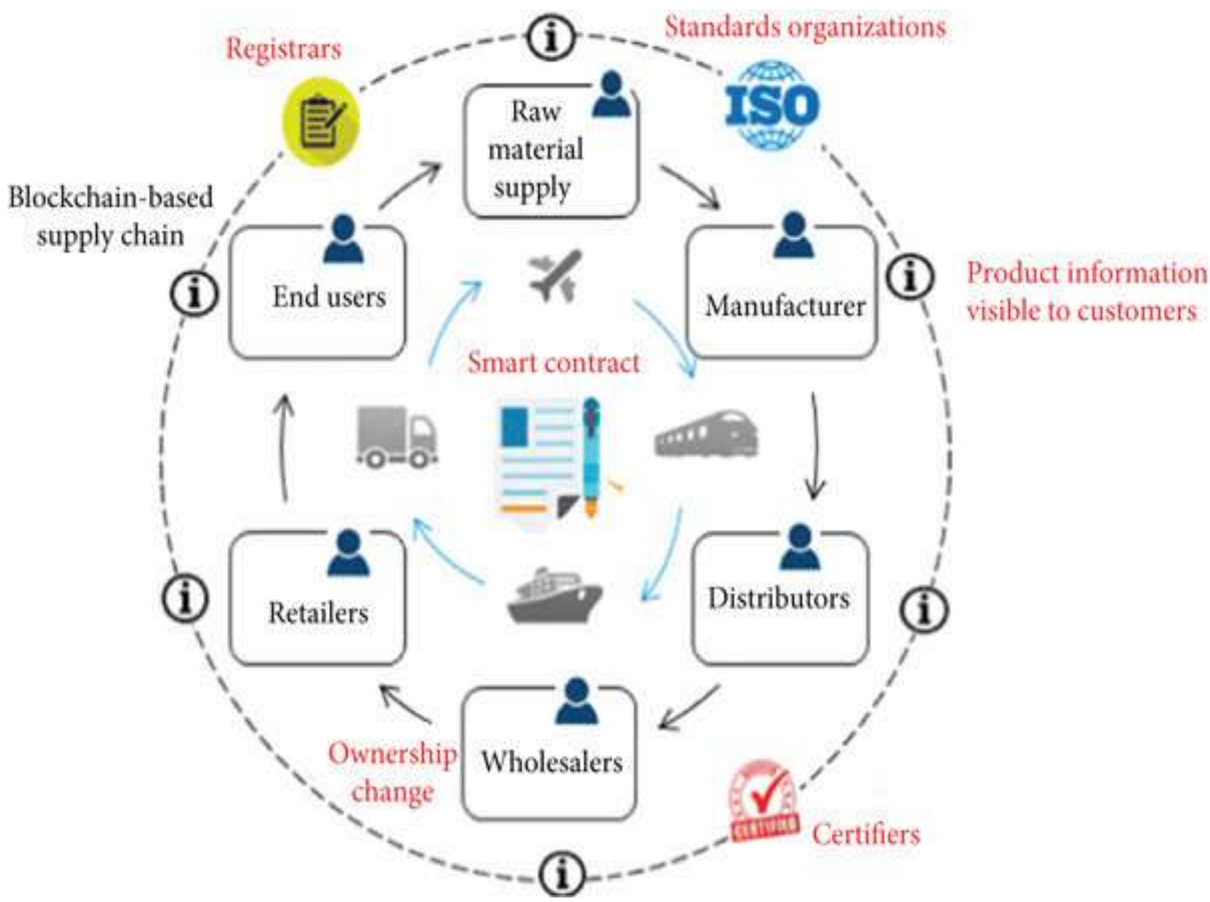

Fig. 3. Blockchain Based Supply Chain

10. Challenges and Limitations

In agri-food logistics, challenges, and limitations of blockchain refer to the technical, economic, organizational, and regulatory barriers that make adoption difficult or constrain its benefits.

10.1 Technical Challenges

Technical challenges of blockchain in agri-food logistics are the system-level limitations and engineering issues that make it hard to design, scale, secure, and integrate blockchain-based traceability solutions.

- Limited rural internet connectivity
- Integration with diverse Iota devices

10.2 Organizational Challenges

Organizational challenges are the people, process, and governance barriers inside and between firms that make blockchain adoption in agri-food chains difficult, even when the technology itself is available.

- Training of farmers
- Resistance to digital transformation
- High initial costs

10.3 Data Quality Issues

Data quality issues are problems with the accuracy, completeness, timeliness, and reliability of information entering a blockchain-based agri-food traceability system, summarized by the “garbage in, garbage out” principle.

Blockchain ensures immutability, but “garbage in = garbage forever”.

10.4 Scalability Problems

Scalability problems are the limitations that prevent blockchain systems from efficiently handling the very high data volumes, transaction rates, and speed requirements of real-world agri-food logistics and global supply chains.

Handling millions of small transactions (milk, fruits, vegetables) requires high throughput.

11. Future Potential and Trends

Future potential and trends of blockchain in agri-food logistics point toward large-scale, integrated, and smarter traceability systems that combine blockchain with IoT, AI, and stricter regulatory frameworks.

11.1 AI + Blockchain for Predictive Quality Analysis

AI + blockchain for predictive quality analysis is the integration of machine learning models with blockchain-based traceability data to forecast food quality, spoilage, or safety risks before they occur, and to act on those predictions in a trusted way.

- Spoilage prediction
- Shelf-life estimation

11.2 Carbon and Sustainability Tracking

Carbon and sustainability tracking is the use of blockchain-based traceability systems to record, verify, and report environmental metrics such as carbon footprint, water use, and sustainable practices at each stage of the agri-food supply chain.

- Recording water usage, emissions, and soil health.

11.3 Integration with National Food Grids

Integration with national food grids means linking blockchain-based traceability systems to a country’s large-scale food distribution and monitoring infrastructure, so that movement, safety, and quality data flow seamlessly across the entire public food ecosystem.

- India’s ONDC, e-NAM, and FPO clusters can integrate Blockchain-based traceability.

11.4 Consumer-Facing Transparency Apps

Consumer-facing transparency apps are mobile or web applications that let shoppers scan a QR code, barcode, or NFC tag on food products to see trusted, supply-chain data (often blockchain-backed) about origin, handling, and certifications.

- QR-based product authenticity verification.

Stage	Color	Icons	Role of AI
Farm	Green	Farm Building, Tractor	Crop Monitoring, IoT Sensors, Smart Agriculture
Transport	Red	Delivery Truck	Route Optimization, Load Monitoring, Supply Chain Alerts

AI Engine	Green	AI Brain	Central Processing, Predictive Analytics
Processing	Black	Factory	Quality Control, Batch Tracking, Food Safety
Retail	Blue	Barcode Scanner, Shopping Cart	Inventory Management, Product Traceability For Consumers

Table 6. Comparative Analysis: Blockchain vs Traditional Systems

12. Recommendations for India's Agri-Food Supply Chains

Recommendations for India's agri-food supply chains focus on building inclusive, standards-based digital traceability with targeted blockchain use, strong governance, and farmer-centric design

1. Adopt consortium Blockchain for commodities (dairy, spices, fruits).
2. Government incentives for FPOs and MSMEs.
3. Training and capacity building for farmers and logistics staff.
4. Standardization of Iota sensors for quality monitoring.
5. Public private partnerships for large-scale adoption.
6. Integration with export inspection councils (APEDA, Coffee Board).

13. Policy Implications

Policy implications of blockchain in agri-food supply chains concern how laws, standards, and institutions must evolve to govern digital traceability, data sharing, liability, and inclusion while using blockchain as regulatory infrastructure

- Blockchain supports FSSAI traceability mandates.
- Enhances India's export competitiveness.
- Enables rapid recall systems to protect public health.
- Helps meet EU/US traceability regulations for food safety.

14. Conclusion

Blockchain-enabled traceability presents a transformative approach to managing Agri-food logistics networks by enhancing transparency, trust, and efficiency. When combined with Iota sensors, smart contracts, and engineering-driven solutions, Blockchain significantly reduces fraud, improves compliance, and optimizes supply-chain performance. Case studies in grape and coffee exports highlight the practical benefits of Blockchain adoption. Although challenges related to cost, training, and interoperability persist, India stands to greatly benefit from structured implementation strategies particularly in high-value agricultural commodities. The future of Agri-food logistics will rely heavily on digital traceability, and Blockchain is positioned as a core enabler of this evolution.

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